Fire Hazards Analysis and Fire Simulation of the Soudan Underground Mine and Fermilab

Prepared for:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 Introduction

Mine Ventilation Services, Inc. (MVS) was contracted to perform ventilation and fire modeling of the Soudan Underground Mine and Fermilab to examine the effects of fires at the facility. The study has been separated into several sections; initial site visit and ventilation survey of the mine and fire modeling. This report details the fire input parameters, preliminary hazards analysis, and fire modeling of the Soudan Mine and Fermilab.

2.0 Fire Considerations

MVS engineers performed certain fire modeling for the Soudan Underground Mine and Fermilab. To conduct fire modeling, it is necessary to evaluate the risk of a fire in the mine. Sources of an underground mine fire at the Soudan Underground Mine and Fermilab may include but not limited to:

1. Diesel Fuel Generator
2. Gas Tanks
3. Electrical Equipment
4. Flammable Products (Paper, Wood, etc.)
5. Electric Powered Train Engine
6. Sump Stations

Each of these areas are to be examined for the potential frequency of the hazard, number of people affected, potential spread of contaminants, and seriousness of each hazard will be determined.

3.0 Preliminary Hazards Analysis

Fire hazard analysis was conducted to determine the potential effects a fire in the underground may have on the facility. The analyses developed are designed to incorporate the highest potential threat generated by a fire. Based on the greatest number of personnel, visitors and potential fire hazards observed the 27 Level was utilized for analyses. A fire around the research labs or tourists destination may result in the greatest number of persons being endangered by the contaminants generated from a fire. Based on the preliminary analysis, fire scenarios were modeled for the diesel fuel generator and electric train engine. Both of these scenarios may yield the greatest threats do their potential size of conflagration and personnel affected by the locations of the fires.

4.0 Calculations of Basic Mine Fires

The fire simulation modeling for the Soudan Underground Mine and Fermilab was simplified with the incorporation of two "basic" mine fires. These fires consist of a diesel fuel generator, located outside of the labs fire doors, and an electric train fire, started at the end of the 27 Level West drift. These "basic" fire calculations are shown in this section to provide a basis for fire modeling at the Soudan Underground Mine and Fermilab.

4.1 Diesel Fuel Generator

The 100 gallon diesel fuel generator located near the base of the shaft was considered for a fire. Under ideal conditions the maximum heat transfer will be approximately 220,042 Btu/min with a contaminant flow rate of approximately 15.35 cfm CO (3.84% of total airflow). The oxygen concentration of O_2 in the exhaust will be approximately 5.67% (0.4 kcfm intake airflow). Assuming ideal combustion and a fully evolved fire the diesel generator has a burn time of approximately 72.0 minutes. Table 1 lists the fire parameters for the diesel fuel generator fire.

Table 1: Fire Parameters for the Diesel Fuel Generator

	Diesel Fuel Generator	
Burn Rate (O_2 rich)	11.35	lb fuel/min
Burn Time	72.03	min
Heat Transfer	220,042	Btu/min
Contaminant Flowrate	15.35	cfm CO
Contaminant Concentration	3.84%	% CO
O_2 Concentration	5.67%	% O_2
Contaminant Production		ft^3/ft^3 O_2
O_2 Concentration Downstream of Fire	18.96%	% O_2

4.2 Electric Powered Train Engine

An electric train engine was considered for a fire located at the end of the 27 Level West fresh air drift. The electric train consists of various flammable materials including electrical sheathing and rubber hoses. Under ideal conditions the maximum heat transfer will be approximately 78,850 Btu/min with a contaminant flow rate of approximately 13.0 cfm CO (12.92% of total airflow). The oxygen concentration of O_2 in the exhaust will be approximately 1.29% (0.1 kcfm intake airflow). Assuming ideal combustion and a fully evolved fire for the single piece of equipment to become engulfed the calculated burn time is approximately 8.9 minutes. Table 2 shows the fire parameters calculated for the electric train.

Table 2: Fire Parameters for the Electric Train

	Electrical Sheathing	
Burn Rate (O_2 rich)	5.63	lb fuel/min
Burn Time	8.89	min
Heat Transfer	78,850	Btu/min
Contaminant Flowrate	13	cfm CO
Contaminant Concentration	12.92%	% CO
O_2 Concentration	1.29%	% O_2
Contaminant Production		ft^3/ft^3 O_2
O_2 Concentration Downstream of Fire	20.87%	% O_2

5.0 Mine Fire Scenarios

5.1 Diesel Fuel Generator Fire Scenario

The 100 gallon diesel fuel generator is located outside of the labs fire doors and approximately 40 feet from the shaft. The area is equipped with a sprinkler system. The diesel generator is illustrated in Figure 1.

Figure 1: Diesel Generator Located on the 27 Level at the Soudan Mine.

For modeling, it was assumed all the fire suppressant systems failed and the diesel fuel generator is able to become fully engulfed. The fire is estimated to burn for approximately 72.0 minutes but the model was executed for two hours to track the fume concentrations through the mine.

After ignition of the fire, the fumes immediately proceed to the shaft to be exhausted. As time progresses, the fire intensity builds forcing increased fume concentrations up the shaft. After approximately 38.0 minutes, air will exhaust from the shaft onto old levels and force fumes into recirculation on the 27 Level. At this point, fresh air being supplied to the 27 Level is being mixed with air contaminated by the fire. After two hours, the modeled fume concentrations immediately exhausting to the shaft from the extinguished fire are reduced but the fume concentration introduced into recirculation on the 27 Level remains throughout the execution. Figure 2 illustrates the source of the diesel fuel generator fire and the fume concentrations throughout the mine after approximately 38.0 minutes, fume fronts are illustrated with the double red triangles. Fumes are shown exhausting from the shaft onto multiple upper levels forcing contaminants into recirculation in Figure 2.

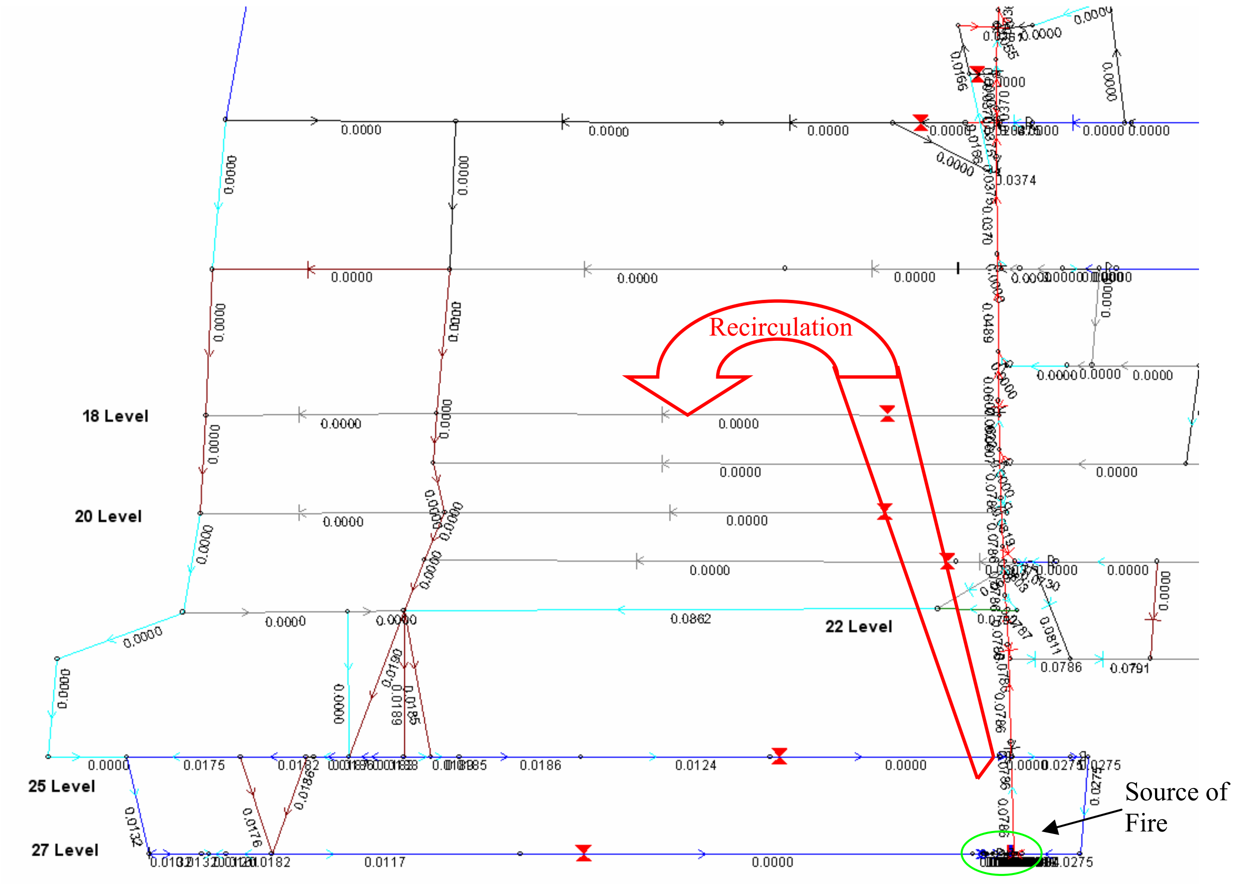

Figure 2: Diesel Fuel Generator Fire and Fume Front after Approximately 38.0 Minutes

After two hours contaminants may still be present on the 27 Level even through the fire is extinguished after approximately 72.0 minutes. Figure 3 illustrates the presence of fume concentrations throughout the mine after two hours.

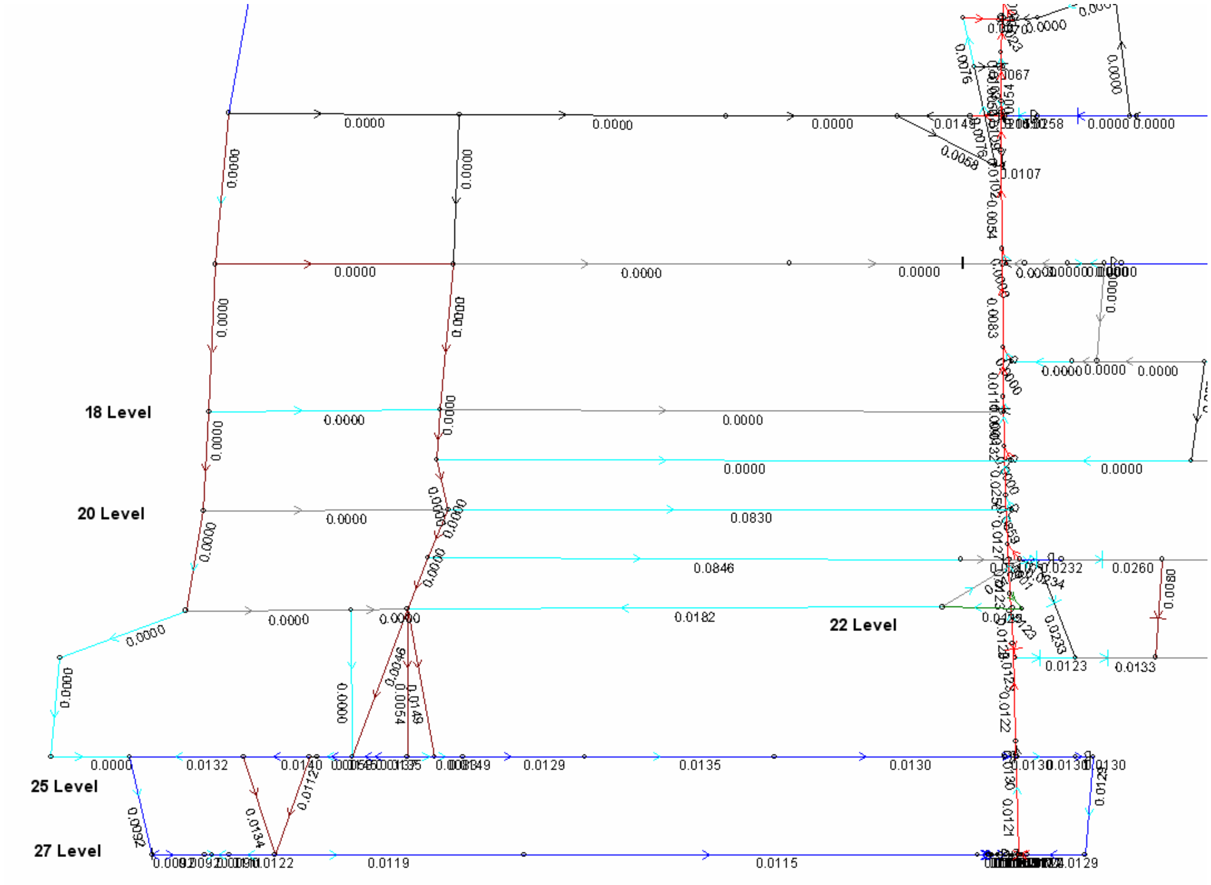

Figure 3: Fume Concentrations of the Diesel Fuel Generator Fire after Two Hours.

5.2 Electric Battery Powered Train Fire Scenario

A fire generated by the electric trains was modeled to illustrate the affects of a fire located in the fresh air supply and upstream the refuge chamber. Assuming the train is able to become fully engulfed and the fire suppressant systems have failed, the electric train will burn for approximately 8.9 minutes.

After the modeled fire was ignited, contaminants generated by the fire move through the 27 Level West drift towards the labs and shaft station. The modeled fume front generated by the fire may reach the shaft station after approximately 14.0 minutes. The contaminants travel up the shaft to be exhausted with some leakage exiting the shaft into old works. The contaminants exhausting the shaft to the old works create recirculation. A primary concern with a fire in this location is the 27 Level West fresh air drift, which personnel may use to access the refuge chamber, is immediately affected by this fire. This fire scenario will force the shaft, the primary escapeway, and the access route to the refuge chamber to be contaminated with fumes. Figure 4 illustrates the fire simulation after approximately 14.0 minutes where the fume front has reached the shaft.

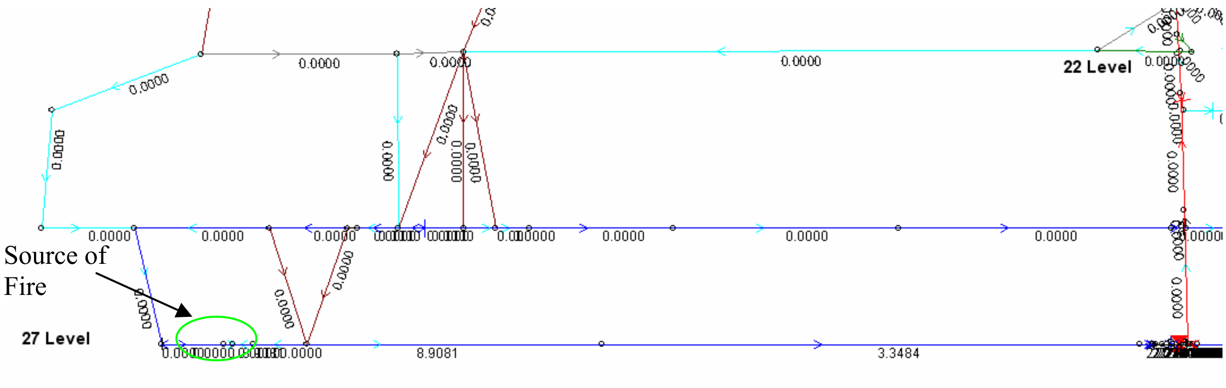

Figure 4: Electric Train Engine Fume Front Reaching the Shaft Station after Approximately 14.0 Minutes.

After two hours, the simulation illustrates contaminants generated by fire may remain in the 27 Level West drift shown in Figure 5.

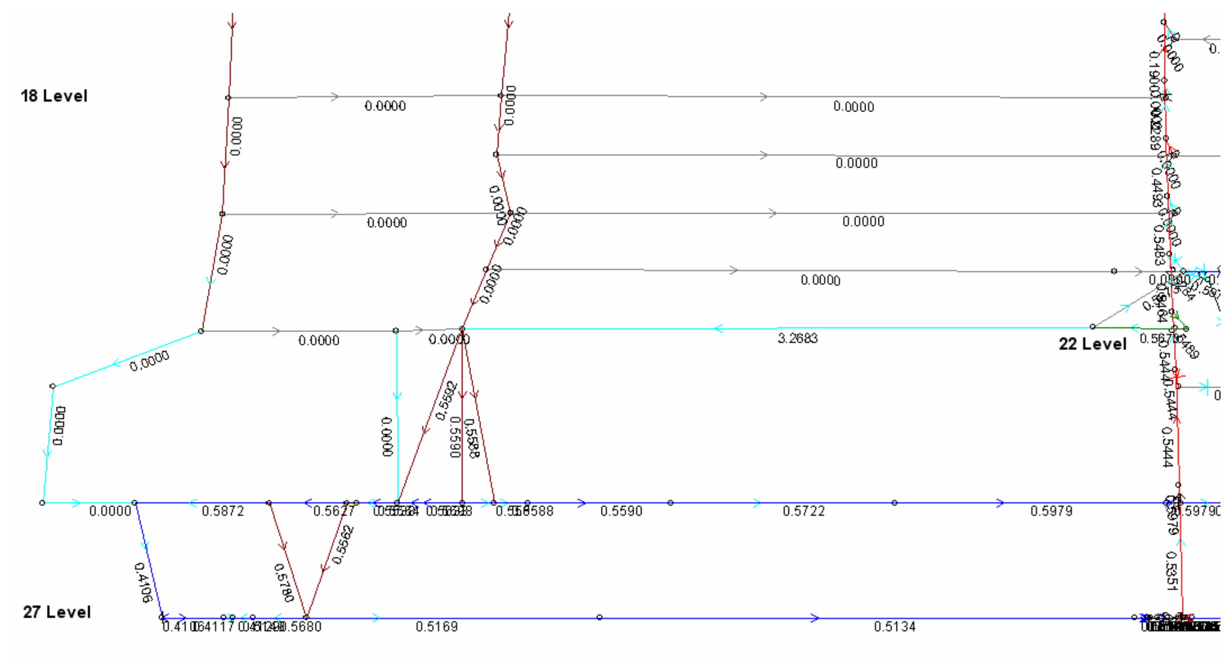

Figure 5: Fume Concentrations of the Electric Train Engine Fire after Two Hours.

6.0 Fire Prevention and Suppression Equipment

The Soudan Underground Mine and Fermilab are outfitted with equipment designed to limit fire hazards. Additionally, fire suppressant equipment has been installed throughout the underground and labs. The supplied lists of fire resistant and prevention equipment used throughout the labs, as well as the fire suppressant systems implemented, are discussed in this section.

The equipment used throughout the labs incorporated various flame resistant components. The electrical vault/transformers are dry cell and all wiring through the lab is incased in conduit. The cables, wires and fiber optics used on the detector are all plenum rated or better which significantly limit the fire load.

Storage and usage of flammable materials in the labs are isolated to particular areas and are equipped with fire suppressants. Metal cabinets are used to store oil, alcohol and paint. The cabinets are kept closed and grounded. Fire resistant paint is used on the wood structures built in the lab; otherwise structures are built with sheetrock.

Throughout the labs fire suppression systems have been implemented. A water sprinkler system is installed with a 50,000 gallons supply from the 25 Level Sump. In the event a smoke alarm goes off or there is flow in the sprinkler system, AC power is cut to everything in the labs and the system is activated. The sprinkler system is installed throughout the labs, offices, storage area and near the diesel generator. Additionally, fire chemical extinguishers are located throughout the labs, on the trains and other levels where work is performed

7.0 Results and Comments

Fire simulation modeling was conducted for the Soudan Underground Mine and Fermilab to evaluate the system and evaluate potential fire scenarios in the underground. Two fires were evaluated for the Soudan Mine, the diesel fuel generator located near the labs and an electric train engine located in the 27 Level West drift. The Soudan Underground Mine is ventilated using a Natural Ventilation System. Results and recommendations regarding a potential fire at the Soudan Underground Mine and Fermilab are discussed in further detail throughout this section.

The fire models developed were designed to illustrate potential scenarios. For both models, it was assumed all fire suppression systems failed and the fires were able to become fully engulfed. The models were developed for two hours which exceeded the sources estimated burn times. By using the extended run time for the scenarios, the contaminants generated by the fires may still be tracked through the underground after the initial source of the fires has extinguished.

Due to the use of natural ventilation, a fire in the underground may potentially have greater affects on the system than a system controlled with a fan. Using a fan, the pressure exhibited through the system is created, forcing the system to remain at a sudo-steady-state throughout the year. A natural ventilation system is affected by the psychrometric properties and will change throughout the year. If a fire occurs in the underground, the barometric pressure and other psychrometric properties in the immediate area may be affected. A fire in the underground will generally have two effects on the ventilation system; first the expansion of the fire with a tendency to create a reduction in airflow and second air becomes heated causing local effects and changes to the natural ventilation system.

A concern with the ventilation system at the Soudan Mine is in the event of a fire, there is a high risk of recirculation through the old works due to the fire pulling air into it and the changing psychrometric properties. Contaminated air may exhaust from the shaft and matriculate through the existing upper levels and mix with the fresh air supply. Due to restricted access to the upper levels, exact knowledge of the ventilation connections through the upper levels is limited. In the event of recirculation, the fresh air supplied to the 27 Level West drift may be contaminated.

In order to limit recirculation, the inaccessible upper levels should be sealed. By installing bulkheads at the shaft station accesses, air may be prevented from exhausting from the shaft and leaking through the old works to the fresh air supply.

With all fires in the underground there are always unpredictable factors that may vary the results of the conflagration. In modeling, the worst case or likely fire scenarios are developed in order to estimate how the system may be affected. However, with any active environment where both personnel and equipment are present, the environmental conditions will change and the fire may result differently. By maintaining the best practices to prevent fires and the ability to control or extinguish a fire quickly, will reduce the possibilities of unfortunate outcomes for both persons underground and the surrounding environment.

Implementation of safety procedures and equipment at the Soudan Underground Mine and Fermilab help to reduce the possibility of a fire or injury. It is noted the labs are equipped with a water sprinkler system and fire doors to isolate the labs from the mine. Electrical transformers are dry cell and the electrical wiring used throughout is either incased in conduit or plenum rated. Fire extinguishers are installed in the labs as well as on the trains and on other levels were electrical equipment is used, such as the sump stations on the 12 Level and 22 Level. Personnel working underground are equipped with self-rescuers and a refuge chamber is located on the 27 Level. The Soudan Underground Mine and Fermilab have implemented extensive equipment for both preventative and suppressant systems to reduce potential fire hazards.

It was noted during the ventilation survey conducted in October 2008; the escapeway ladder between the 27 Level and 25 Level in the shaft was inaccessible. A secondary ladder must be used at the end of the 27 Level West drift for egress between the 27 Level and 25 Level. Due to the shaft is being used to enter and exit the Soudan Underground Mine and Fermilab; it is recommended the ladder-way within it be maintained for personnel to use in the event the cage is inoperable.

In the event of an emergency, personnel working on levels other than the 27 Level must be notified. Should a fire occur in the underground a warning system must be activated to notify personnel to dawn their self-rescuers and evacuate the mine. Personnel working on other levels are limited to the shaft for egress and should have an emergency plan incorporated. The plan needs to establish forms of notification and emergency procedures. In the event of an emergency, the total number of persons underground and their locations should be known by the surface. This will assist in the assurance that all persons are accounted for if there is an emergency.

References

Anderson, B., Beaty, J., Meier, J., Miller, W., and Wiermaa, D., October 17, 2007, "Soudan Underground Mine State Park and Soudan Lab Air Flow Measurements," Soudan Underground Laboratory.

McPherson, M.J., 1993, "Subsurface Ventilation and Environmental Engineering," Chapman and Hall Publishing, 905 pp.

APPENDIX A

Fire Analysis

Summary of Results Table - Diesel Fuel Generator

	Diesel Fuel Generator	
Burn Rate (O_2 rich)	11.35	lb fuel/min
Burn Time	72.03	min
Heat Transfer	220,042	Btu/min
Contaminant Flowrate	15.35	cfm CO
Contaminant Concentration	3.84%	% CO
O_2 Concentration	5.67%	% O_2
Contaminant Production		ft^3/ft^3 O_2
O_2 Concentration Downstream of Fire	18.96%	% O_2

Input Parameters		
Fuel Rich Airflow:	0	cfm
Oxygen Rich Airflow:	400	cfm
Air Density:	0.78	lb/ft^3
Heating Value of Diesel Fuel:	19390	Btu/lb
Gallons of fuel:	100	gal

Results (TF5)		
Burn Rate (O_2 rich)	11.35	lb fuel/min
Min Burn Time	72.0	min
Heat Transfer	220,042	Btu/min
Contaminant Flowrate	15.3	cfm CO
Contaminant Concentratic	3.84%	% CO
O_2 Concentration	5.67%	% O_2
Contaminant Production		ft^3/ft^3 O_2

Diesel Fuel Component Fractions, from Figure 6 of "Integrated Approach"

fractional values in weight percent

Fuel	Components Major hydrocarbon	Isopar G C_4H_9	Napar-10 $C_{10}H_8$	Norpar-12 $C_{14}H_{30}$	Isopar L C_4H_9	Decalin $C_{10}H_8$	Exxsol D80 C_5H_{12}	Norpar-13 $C_{14}H_{30}$	Norpar-15 $C_{14}H_{30}$	Perm101a $C_4H_{10}N_2$?	ESN-60 Wax $C_7H_{10}N_2$ *	Isopar V C_4H_9	Exxsol D130 C_5H_{12}
A	NC=4		0.075			0.07			0.41	0.445			
B	NC=8	0.03	0.02		0.075			0.29		0.14	0.165	0.25	0.03
C	NC=10	0.04	0.01		0.08		0.08	0.15	0.13	0.16	0.13	0.14	0.08
D	NC=12	0.04	0.01	0.005	0.08		0.075	0.15	0.13	0.16	0.13	0.14	0.08
TF5	optimized	0.067334	0	0.382463	0.066333	0	0.2	0.008768	0.0087685	0	0	0.066333	0.2

Possible Chemical Reactions

	Hydrocarbon		Oxygen		carbon dioxide		water vapor		oxides of nitrogen		Moleweight of hydrocarbon
1)	2	C_4H_9 +	12.5	O_2 -->	8	CO_2 +	9	H_2O			57
2)	1	$C_{10}H_8$ +	12	O_2 -->	10	CO_2 +	4	H_2O			128
3)	1	$C_{14}H_{30}$ +	21.5	O_2 -->	14	CO_2 +	15	H_2O			198
4)	1	C_5H_{12} +	8	O_2 -->	5	CO_2 +	6	H_2O			72
5)	1	$C_4H_{10}N_2$ +	8.5	O_2 -->	4	CO_2 +	5	H_2O +	2	NO_2	86
6)	1	$C_7H_{10}N_2$ +	11.5	O_2 -->	7	CO_2 +	5	H_2O +	2	NO_2	122

1) Stoichiometric ratios (g air / g hydrocarbon)

		Molwt (g/mol)	Moles O_2	Stoich. Ratio
Isopar G	C_4H_9	57	12.5	30.51
Napar 10	$C_{10}H_8$	128	12	13.04
Norpar 12	$C_{14}H_{30}$	198	21.5	15.11
Isopar L	C_4H_9	57	12.5	30.51
Decalin	$C_{10}H_8$	128	12	13.04
Exxsol D80	C_5H_{12}	72	8	15.46
Norpar 13	$C_{14}H_{30}$	198	21.5	15.11
Norpar 15	$C_{14}H_{30}$	198	21.5	15.11
Perm101a	$C_4H_{10}N_2$	86	8.5	13.75
ESN-60 Wax	$C_7H_{10}N_2$	122	11.5	13.11
Isopar V	C_4H_9	57	12.5	30.51
Exxsol D130	C_5H_{12}	72	8	15.46

Fuel Rich Airflow:	0	cfm
Oxygen Rich Airflow:	400	cfm
Air Density:	0.78	lb/ft^3
Heating Value of Diesel Fuel:	19390	Btu/lb

Fuel A:	14.205	g air / g fuel
Fuel B:	20.026	g air / g fuel
Fuel C:	18.672	g air / g fuel
Fuel D:	18.670	g air / g fuel
TF5:	18.329	g air / g fuel

5) TF 5 Optimization

	Normal Parafins		Iso-Parafins		Cyclo-parafins	
	Norpar 12	0.382	Isopar G	0.067	Napar 10	0.000
	Norpar 13	0.009	Isopar L	0.066	Decalin	0.000
	Norpar 15	0.009	Perm101a	0.000	Exxsol D80	0.200
	ESN60 Wa	0.000	Isopar V	0.066	Exxsol D130	0.200
		0.4		0.2		0.4
Set totals equal to:		0.4		0.2		0.4

Objective function: Max TF5 air:fuel ratio

ST:

Mass fraction of normal parafins =	0.4
Mass fraction of iso-parafins =	0.2
Mass fraction of cyclo-parafins =	0.4
each component >=0	

Summary of Results Table - Electric Train Engine Fire

	Electrical Sheathing	
Burn Rate (O_2 rich)	5.63	lb fuel/min
Burn Time	8.89	min
Heat Transfer	78,850	Btu/min
Contaminant Flowrate	13	cfm CO
Contaminant Concentration	12.92%	% CO
O_2 Concentration	1.29%	% O_2
Contaminant Production		ft^3/ft^3 O_2
O_2 Concentration Downstream of Fire	20.87%	% O_2

Input Parameters	
Fuel Rich Airflow:	0 cfm
Oxygen Rich Airflow:	100 cfm
Air Density:	0.78 lb/ft^3
Heating Value of Tires:	14015 Btu/lb
	1
Weight of Electrical Sheathing	50 lb

Results		
Burn Rate (O_2 rich)	5.63	lb fuel/min
Min Burn Time	8.9	min
Heat Transfer	78,850	Btu/min
Contaminant Flowrate	12.9	cfm CO
Contaminant Concentration	12.92%	% CO
O_2 Concentration	1.29%	% O_2
Contaminant Production		ft^3/ft^3 O_2

Components of, by mass			molwt
Styrene Butadiene Rubber (SB	$(C_6H_9)C_6H_5$	46.80%	158
Carbon Black	C	45.50%	12
Sulfur	S	1.20%	32
Ash + other volatiles		6.50%	

Oxygen Consuming Reactions						
1 $(C_6H_9)C_6H_5$ +	9.5	O_2 -->	12	CO +	7	H_2O
1 C +	1	O_2 -->	1	CO_2		
1 S +	1	O_2 -->	1	SO_2		

Stoichiometric Ratios:

	Molwt (g/mol)	Moles O_2	Stoich. Ratio
$(C_6H_9)C_6H_5$	158	9.5	8.37
C	12	1	11.59
S	32	1	4.35

SR of Tires: 9.243 g air / g fuel

2) Determine Burn Rate & Heat Transfer

Fuel rich Case Max Burn rate = 0.000 lb / min

Qin * density / air:fuel ratio

Oxygen Rich Case Max Burn rate = 5.63 lb / min

Heat Transfer = 78,850 Btu/min

(assumes 50% over ventilated)

(Qin / 1.5) * density / air:fuel ratio

Burn rate (D38) * Heating value

Burn time = 8.9 min

3) Find contaminant variables for Tires, CO as the contaminant

Mass flowrate of oxygen: Fuel-rich 0 lb O_2/min

Oxygen-rich 16.38 lb O_2/min

Carbon Black: $2\,C + 1.5\,O_2 \rightarrow CO + CO_2$

Assume the following ratio of components formed in the fire: $\frac{CO}{CO_2}$ CO 0.5, CO_2 0.5

O_2 needed to burn Carbon Black: Fuel-rich 0.00 lb O_2/min

Oxygen-rich 9.35 lb O_2/min

$$.455\,C + 1.5\,X\,O_2 \rightarrow Y\,CO + Z\,CO_2$$

$X = 0.455 \times 1.5 \times (32/12) =$ 1.820 lb O_2 consumed / lb

$Y = (Ratio_{CO}) \times 0.455 \times 1.5 \times (28/12) =$ 0.796 lb CO produced / lb

Mass Flowrate of CO: = (fuel rich lb O_2/min)* lb CO / lb O_2= 0.00 lb CO/min

= burn rate * lb CO / lb tires = 4.48 lb CO/min

SBR: $(C_6H_9)C_6H_5 + 9.5\,O_2 \rightarrow 12\,CO + 7\,H_20$

O_2 needed to burn SBR: Fuel-rich 0.00 lb O_2/min

	Oxygen-rich	3.96	lb O_2/min	

$$0.468\ (C_6H_9)C_6H_5 + 9.5\ X\ O_2 \rightarrow 12\ Y\ CO + 7\ Z\ H_20$$

X =0.468 × 9.5×(32/158) =	0.900	lb O_2 consumed
Y =0.468 × 12×(28/158) =	0.995	lb CO produced

Mass Flowrate of CO:		= (fuel rich lb O_2/min)* lb CO / lb O_2=	0.00	lb CO/min
		= burn rate * lb CO / lb tires =	5.60	lb CO/min
Total mass flowrate of CO:	Fuel-rich		0.000	lb CO/min
	Oxygen-rich		10.08	lb CO/min
Volume Flowrates:	Fuel-rich	= mass flow / density =	0.0	cfm CO
	Oxygen-rich	= mass flow / density =	**12.9**	**cfm CO**
Concentration:	**Oxygen-rich =** Q_{CO} / Q_{in}		**12.92%**	
Contaminant Production	**Fuel rich**	$Q_{CO}/(Q_{in}*.21)$		$ft^3/ft^3\ O_2$

4) Determine O_2 Concentration of Exhaust

	Mass	O_2 consumed	
Mass SBR =	0.468 lb/lb tire	0.900 lb/lb tire	
Mass C =	0.455 lb/lb tire	1.820 lb/lb tire	
Mass S =	0.012 lb/lb tire	0.012 lb/lb tire	$S + O_2 \rightarrow SO_2$
	Total O_2 consumed	2.732 lb/lb tire	

O_2 consumed by combustion = O_2 consumed x burn rate =	15.4	lb O_2/min
Mass flowrate into the fire =	16.38	lb O_2/min
Mass flowrate out of the fire =	1.0	lb O_2/min
Flowrate of O_2 =	1	cfm O_2
Concentration of O2 in exhaust =	**1.29%**	